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THE DESIGN AND DYNAMIC CALIBRATION OF A PRESSURE TRANSDUCER SYSTEM FOR UNSTEADY PRESSURE MEASUREMENTS

By

R. F. Austin and G. C. Trail, Jr.

Propulsion Wind Tunnel Facility

ARO, Inc.

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ARNOLD ENGINEERING DEVELOPMENT CENTER

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ARO, Inc.

a subsidiary of Sverdrup and Parcel, Inc.

March 1963

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ABSTRACT

A specialized method is discussed for adapting conventional flush-mounted pressure transducers for measurement of unsteady pressures to 1000 cps. Details of the calibration apparatus are presented together with the measured effects of transducer system geometry and environmental pressure level on the dynamic response of the system.

PUBLICATION REVIEW

This report has been reviewed and publication is approved.

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NOMENCLATURE

a	Speed of sound at environmental temperature, ft/sec
c_o	Acoustical conductivity of an orifice, ft/sec
f	Frequency, cps
f_o	Acoustical natural frequency of Helmholtz resonator, cps
L	Inlet orifice length, ft
R	Inlet orifice radius, ft
t_r	Rise time from 10 to 90 percent of a pressure step input, sec
V	Inlet volume, ft^3
V_c	Amplitude response of pressure cell, volts
V_s	Amplitude response of standard pressure transducer, volts

1.0 INTRODUCTION

Special techniques must be employed to measure unsteady pressures associated with various aerodynamic phenomena in fluid flow and on bodies immersed in a fluid flow environment. Because flush diaphragm-type transducers are generally available, it is desirable to adapt them for measuring unsteady pressures over a wider range of frequencies than that for which this type transducer is normally suited. When mounted directly in a measurement surface, most flush diaphragm-type transducers are capable of accurately measuring unsteady pressures at frequencies up to 10 percent of the undamped natural frequency of the diaphragm. The range of frequencies of unsteady pressures that can be measured with this type transducer is therefore limited by the natural frequency of the transducer diaphragm. In some applications, it is impossible to mount transducers directly in the measurement surface. Where small radius of curvature measurement surfaces are involved (i.e., small wind tunnel models), the transducer diaphragm size can create unacceptable surface discontinuities and also lead to inaccuracies in defining the model location being investigated. When mounted directly, the transducer is susceptible to mechanical damage. Another problem which exists is that some aerodynamic phenomena contain frequency components that can cause destructive resonance of the transducer diaphragm. Provisions must be made for mounting transducers which obviate these problems.

Many of the problems associated with measurement of unsteady pressures have been investigated. The results of several of these investigations are given in Refs. 1 through 6. Particular attention should be given to Refs. 1 and 2, which cover a broad range of problems associated with practical systems for measurement of unsteady pressures.

There still exists a need to develop and adopt a universal standard transducer to be used in comparative dynamic calibration of pressure transducers. Secondly, random pressure generators need to be developed, since many unsteady pressure phenomena are random in nature and because sinusoidal calibrations for measurement of such phenomena are open to question. Neither of these problems has been treated in the present investigation.

The purpose of this paper is to present the methods employed in the design and dynamic calibration of a pressure transducer system capable of

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measuring unsteady pressures in the frequency range from 5 to 1000 cps. The effect of transducer system geometry and environmental pressure level on the dynamic response characteristics of the system are presented as the ratio of transducer system output to the output of a standard as a function of frequency.

The investigation reported herein was conducted in the Instrument Laboratory of the Propulsion Wind Tunnel Facility (PWT), Arnold Engineering Development Center (AEDC), Air Force Systems Command (AFSC).

2.0 APPARATUS AND PROCEDURE

2.1 PRESSURE CELL SYSTEMS

The transducers adapted for unsteady pressure measurements were 7.5-psi Consolidated Electrodynamics Corporation (CEC) 4-312 and Statham Laboratories P-222 transducers. Both transducers are conventional, flush diaphragm, differential pressure transducers and are 1/2 and 1/4 inch in diameter, respectively. The approximate undamped natural frequencies of these transducers are 5000 cps for the 4-312 and 7000 cps for the P-222.

The transducers were mounted in cell enclosures as shown in Figs. 1 through 3. These enclosures provide protection to the delicate sensing diaphragm and a means of mounting the transducer which avoids preloading the diaphragm. The mounting also provides some isolation of the transducer from vibrations of the mounting surface. The basic cell enclosure consists of an inlet orifice and volume as shown in Fig. 1. The inlet orifice limits the area over which the pressure measurement is made to the specific location of the orifice. In certain applications, this can be of utmost importance. An example is seen in testing small wind tunnel models. The transducer diaphragm area may be large enough to impose serious surface discontinuities that would not appear on the full-scale prototype. The action of the orifice on the unsteady pressure being measured is to restrict the pressure amplitude transmitted to the transducer at certain frequencies. By proper choice of inlet orifice diameter and cell inlet volume, unsteady pressures at frequencies of or near the natural frequency of the transducer diaphragm can be attenuated to a low enough energy level to prevent destruction of the transducer caused by diaphragm resonance.

When placing a transducer in an enclosure containing an inlet orifice and volume, care must be taken that the acoustical natural frequency and

its harmonics do not match the mechanical natural frequency of the transducer diaphragm. If this happens, the transducer can be destroyed by resonance. It is desirable that the acoustical natural frequency of the cell orifice-volume combination be above that of the transducer. An approximate method for calculating the acoustical natural frequency of such a system is given in Refs. 7 and 8 by the relationship

$$f_o = \frac{a}{2\pi}\sqrt{\frac{c_o}{V}}$$

The orifice conductivity may be determined by the following relationship:

$$c_o = \frac{\pi R^2}{L + \frac{\pi R}{2}}$$

To provide a reference pressure for the transducers, the pressure cells are equipped with tubing systems as shown in Figs. 4 and 5. In both instances, the reference pressure is a damped mean of the unsteady pressure being measured by the pressure cell. The unsteady pressure is damped by a length of tubing which acts as a low pass acoustic filter. At sufficiently high frequencies the tubing will not transmit the unsteady pressures and, therefore, provides a damped mean for the reference pressure. When the reference system shown in Fig. 5 is employed, the pressure cell response may be adversely affected by changes in inlet volume caused by the volume of the reference pressure tubing system. In general, the reference pressure tubing diameter should be kept small to minimize the effect on inlet volume.

This type reference system permits measurement of unsteady pressures over a large range of steady-state pressure levels. The highest absolute pressure environment in which the pressure cell can be used is limited only by the pressures that the transducer case can tolerate. The reference systems also offer the advantage of using the lowest range transducer possible to accommodate the peak to peak unsteady pressure, and ensures that the highest degree of pressure sensitivity is maintained. The absolute value of the reference pressure is measured by a separate steady-state pressure transducer.

2.2 STEP INPUT TUBE

The step input tube provided a means of applying a step pressure input to a pressure cell system. The tube consists of two sections separated by a diaphragm. A pressure difference was developed across the diaphragm, and after a steady-state condition was attained, the diaphragm was ruptured

and the pressure allowed to equalize in the tube. Details of the step input tube are shown in Figs. 6 and 7. The response of the pressure cell to the pressure step input was observed with an oscilloscope and recorded photographically. The time required for the pressure cell output to rise from 10 to 90 percent of the original pressure step input amplitude is the rise time, t_r, for the system. This rise time is analogous to the rise time of an electronic amplifier (a device which acts as an electronic low pass filter at some frequencies), since the dynamical equation which describes the response of a tube is the same as that for an amplifier. The rise time is inversely proportional to the frequency at which the amplifier response is down to 70.7 percent of the mid-range dynamic response. This relationship, for a first or second order system which exhibits small overshoot in its response to a step input, is expressed by the empirical relationship (see Ref. 9)

$$f = \frac{0.35}{t_r}$$

Measurement of the pressure cell rise time permitted calculation of the frequency below which the pressure cell reference system ceased to effectively damp fluctuations of the reference pressure.

2.3 PISTON CALIBRATOR

The piston calibrator system was designed to generate an approximate sinusoidal wave form at frequencies from 5 to 85 cps. Details of the piston calibrator are presented in Figs. 8 and 9. The calibrator was fashioned from a modified, single cylinder, model aircraft engine of 0.60-cubic-inch displacement. The original ported cylinder sleeve was replaced by a solid sleeve, and a special cylinder head was employed for mounting the pressure cell and standard transducer. The cylinder head also provided for varying the compression ratio of the engine. This allowed varying the maximum root-mean-square pressure level in the cylinder over a range from 1 to 3.0 psi. The calibrator was driven by an electric motor and simple gear trains. This arrangement provided calibrator speeds up to 5100 rpm, which corresponds to 85 cps. The resulting output wave forms generated by the piston calibrator are shown in Fig. 10. The reference wave forms in Fig. 10 are electronically generated sine waves at the indicated frequencies.

To obtain the dynamic response characteristics of the pressure cell and reference system, the cell output was compared to that of a standard. The standard used with the piston calibrator was a CEC 4-312 pressure transducer flush mounted in the cylinder head. This transducer has a flat dynamic response in the zero to 500-cps range when flush mounted.

2.4 STANDING WAVE TUBE

To calibrate the pressure cells at frequencies higher than those attainable with the piston calibrator, it was necessary to adopt another system. This system consisted of a tube of 3.20-inch inside diameter and 36-inch length. One end of the tube contained a horn driver and the other a plate in which the pressure cell being tested and a standard microphone were mounted. The horn driver was excited with a 250-watt amplifier which derived its input signal from a variable frequency oscillator. Details of the standing wave tube and its associated equipment are shown in Figs. 11 through 14. The fundamental resonant frequency of an air column is determined by its length. The fundamental resonant frequency of this standing wave tube was measured as 180 cps, which corresponds to a wave length of 72 inches. The tube length was fixed at 36 inches, which permits its use at 180 cps and at harmonics of 180 cps. At these frequencies the highest pressure obtainable exists at the end of the tube where the pressure cell and the standard microphone are mounted.

Above 5000 cps the signal to noise ratio becomes low. Within this limit, the standing wave tube develops root-mean-square acoustic pressures ranging from 0.003 to 0.03 psi, depending on frequency. Because the acoustic power available with this system is low, care must be taken to eliminate spurious output from both the pressure cell and the standard microphone. This effect is caused primarily by mechanical vibration of the end plate mounting. This vibration is induced by mechanical coupling of the horn driver to the end plate through the wall of the tube and also by acoustic excitation. Most pressure transducers are sensitive to acceleration; thus, vibration of the transducer diaphragm can induce large errors when low level unsteady pressures are being measured. The most effective means of eliminating these problems at low frequencies in the standing wave tube was to employ a heavy end plate with the most rigid cell mounting possible. The effect of vibration may be evaluated by measuring pressure cell output at each frequency twice, once with the inlet orifice open and then with the orifice plugged.

Another problem encountered with the standing wave tube is that the acoustic output of such a system is high in harmonic content. Even though a reasonably pure sinusoid is fed into the horn driver, the standing wave tube and the transducer diaphragm tend to resonate at several harmonics of the input signal. An electrical band pass filter was used to filter the output of the pressure cell and the standard microphone. The upper and lower cutoff frequencies were set at 1.5 f and 0.5 f, respectively, where f is the oscillator input frequency to the horn driver. This permitted evaluation of the response of the pressure cell to a discrete frequency. The dynamic response characteristics of the pressure cell were obtained

by comparing the cell output to that of a standard microphone. The microphone used was a MASSA Type 213 piezoelectric microphone which has a nominal frequency response of ±1 db from 50 to 12, 000 cps.

3.0 DATA REDUCTION

The dynamic response of a pressure cell is presented as the ratio of pressure cell output, V_c, to the output of some standard, V_s. The standard has a nominal linear or flat amplitude vs frequency characteristic. The output signals from both the pressure cell and the standard appear as voltages. The absolute magnitudes of the calibration pressure and of the output signals are eliminated, and have no real significance to the response characteristics of the cell.

4.0 DISCUSSION OF RESULTS

Data are presented which demonstrate the effect of inlet orifice diameter and volume and environmental pressure level on the dynamic response of a pressure cell. These data are presented to serve as a guide in the design of pressure cells for particular applications.

Results were obtained with the pressure cell configuration shown in Figs. 1 through 3. A CEC 4-312 transducer referenced to atmospheric pressure was placed in the cell and tested in the standing wave tube. The effect of orifice diameter on the dynamic response of the cell with a constant inlet volume is shown in Fig. 15. These results show that resonance peaking of the transducer diaphragm may be sharply attenuated by employing a sufficiently small orifice diameter. At frequencies approaching the natural frequency of the transducer, the amplitude response becomes larger as orifice diameter is increased. At the limiting case where the orifice diameter equals the diameter of the transducer, the diaphragm will resonate freely at its natural frequency. This can result in destruction of the transducer. The action of the orifice is to transmit low frequencies and impede the high frequencies (short wave lengths).

The effect of inlet volume size on the dynamic response of the cell with a constant diameter orifice is shown in Fig. 16. These results show that for a constant orifice diameter the cell response decreases at frequencies above 1000 cps as inlet volume size is increased. At frequencies below 1000 cps the effect of inlet volume size on cell response is small.

The effect of environmental pressure level on the response of a typical cell is illustrated in Fig. 17. These data were obtained by evacuating the standing wave tube to the indicated pressure levels and show that cell response can be adversely affected by environmental pressure level. This important effect must be considered in any application of the pressure cell. Similar results were obtained in the investigation reported in Ref. 1. The effect of environmental pressure level on pressure cell response was predicted from the analytical treatment presented in Ref. 1 and was verified by experimental results during that investigation.

The results presented in Figs. 15 through 17 for frequencies above 3000 cps contain spurious vibrational response components generated by vibrations of the standing wave tube end plate.

Details of a pressure cell adapted for unsteady pressure measurements on wind tunnel models are presented in Figs. 18 through 20. The lower part of Fig. 20 demonstrates the method used for determining the cutoff frequency of the combined pressure cell and reference system. The rise time, t_r, shown in Fig. 20 was obtained with the step input tube that was discussed previously in Section 2.2. Measurement of the system rise time permitted calculation of the lowest frequency below which the pressure cell reference system ceased to effectively damp fluctuations of the reference pressure.

The pressure cell output wave forms presented in Fig. 21 were obtained with the piston calibrator that was discussed in Section 2.3. These wave forms were obtained for the pressure cell configuration shown in Fig. 20. The time histories in Fig. 21 demonstrate that the pressure cell will reproduce sinusoidal pressure variations over the range of frequencies presented. The high frequency ripple superimposed on the standard transducer output wave form in Fig. 21a is 60 cps electrical noise.

The dynamic response characteristics of the pressure cell configuration in Fig. 20 are presented in Fig. 22 for frequencies from 11 to 7000 cps. These data were obtained with the piston calibrator and the standing wave tube. The vibrational response was evaluated by plugging the orifice and repeating the test over the entire range of frequencies. The cell response was unaffected by vibrational excitation below 2000 cps. At frequencies above 2000 cps the pressure cell response to vibrational excitation becomes progressively higher as frequency is increased. The results presented in Fig. 22 show that the pressure cell system has a flat dynamic response from 11 to 940 cps for both the 0.030-inch- and 0.100-inch-diameter inlet orifice.

5.0 CONCLUSIONS

Investigations were conducted to determine methods for design and dynamic calibration of pressure transducer systems for unsteady pressure measurement. These investigations lead to the following conclusions.

1. Relatively simple apparatus may be employed to obtain sinusoidal dynamic calibrations of pressure transducers.
2. Pressure cell mounting geometry can be designed to prevent destructive mechanical resonance of the pressure transducer diaphragm and large discontinuities in the measurement surface.
3. Pressure cell response is adversely affected by decreasing environmental pressure level (density).
4. Pressure cell response is related to so many mechanical characteristics of the system (inlet orifice diameter and volume size, reference tubing geometry, etc.) that each cell and its associated reference system should be subjected to dynamic calibration before use.

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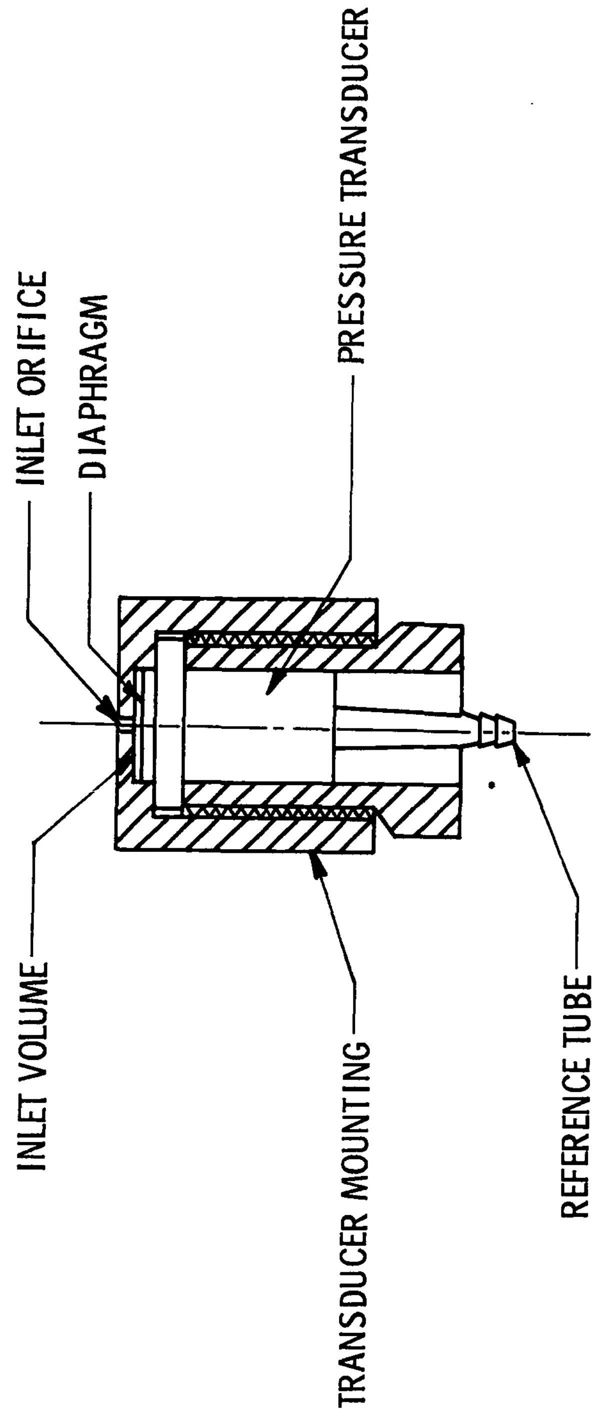

Fig. 1 Pressure Cell Nomenclature

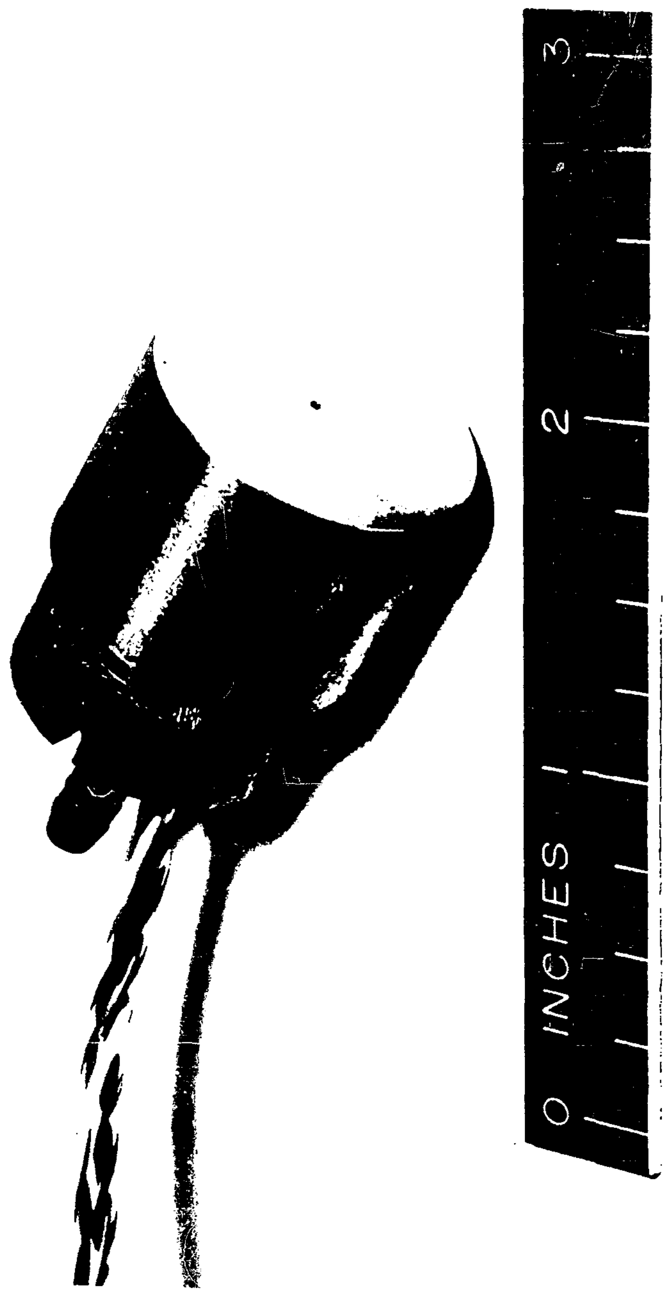

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Fig. 2 Pressure Cell Assembled

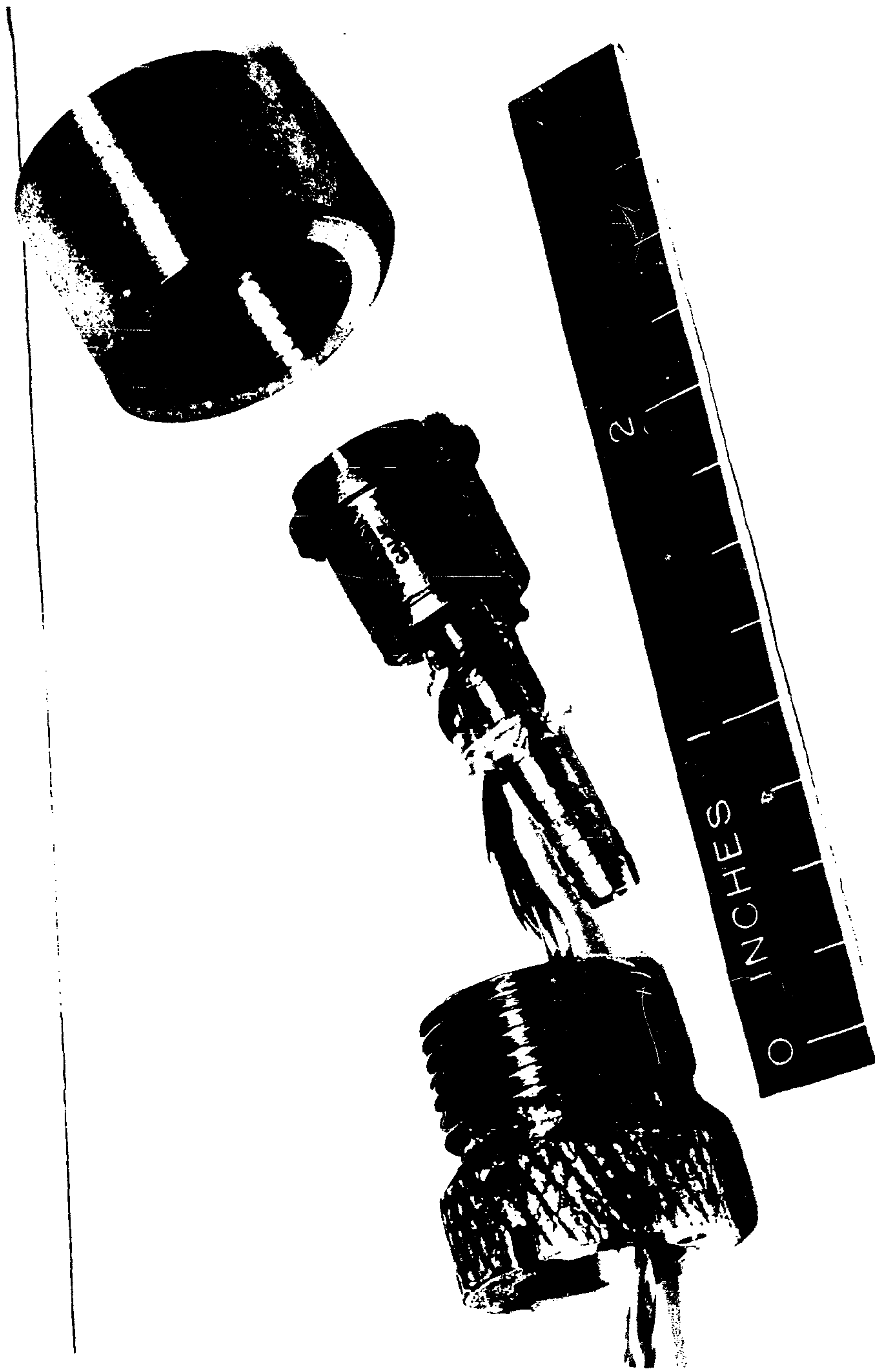

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Fig. 3 Pressure Cell Disassembled

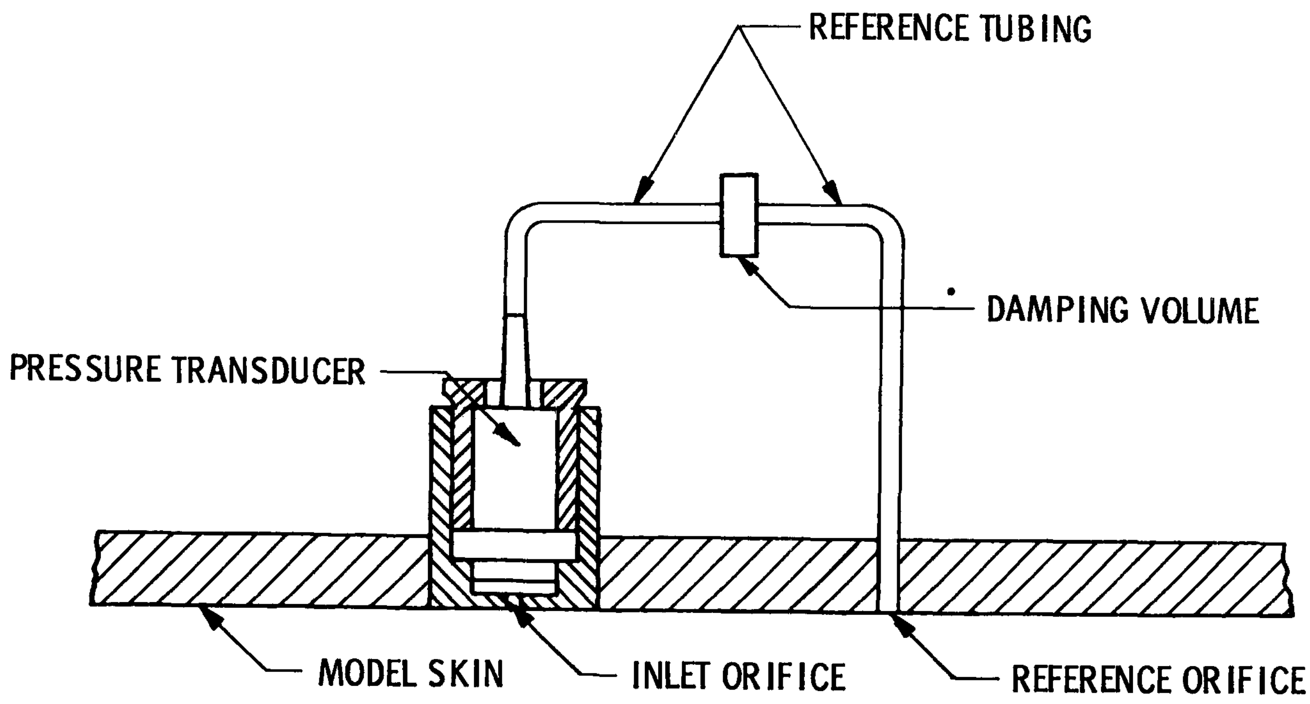

Fig. 4 Details of Off-Set Reference Pressure System

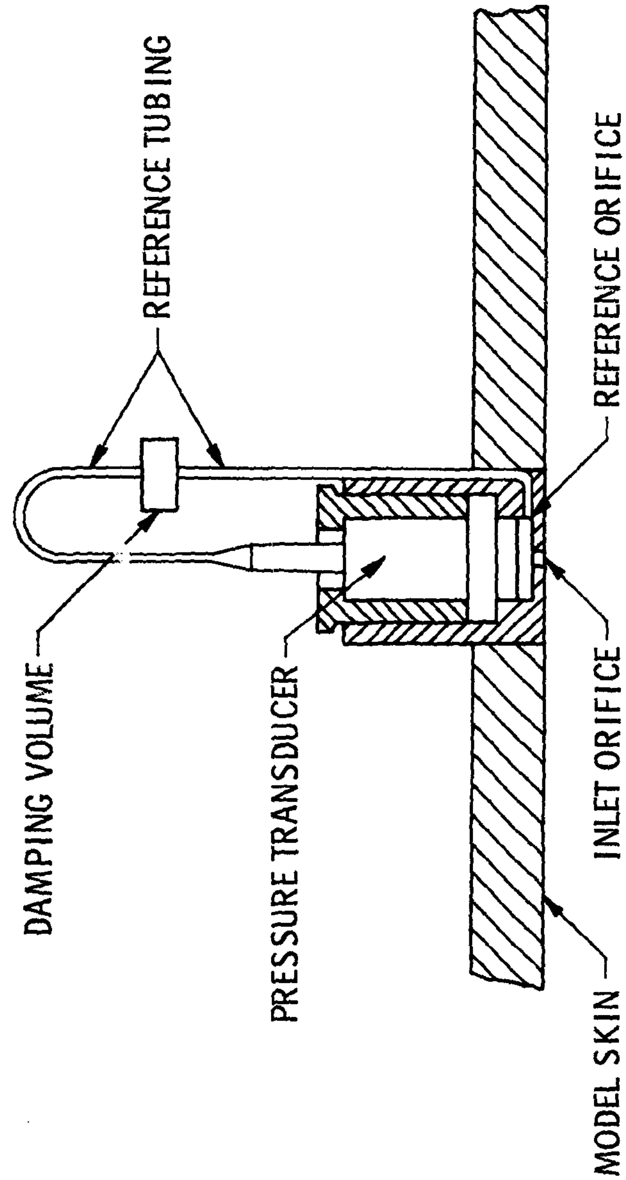

Fig. 5 Details of Inlet Volume Reference Pressure System

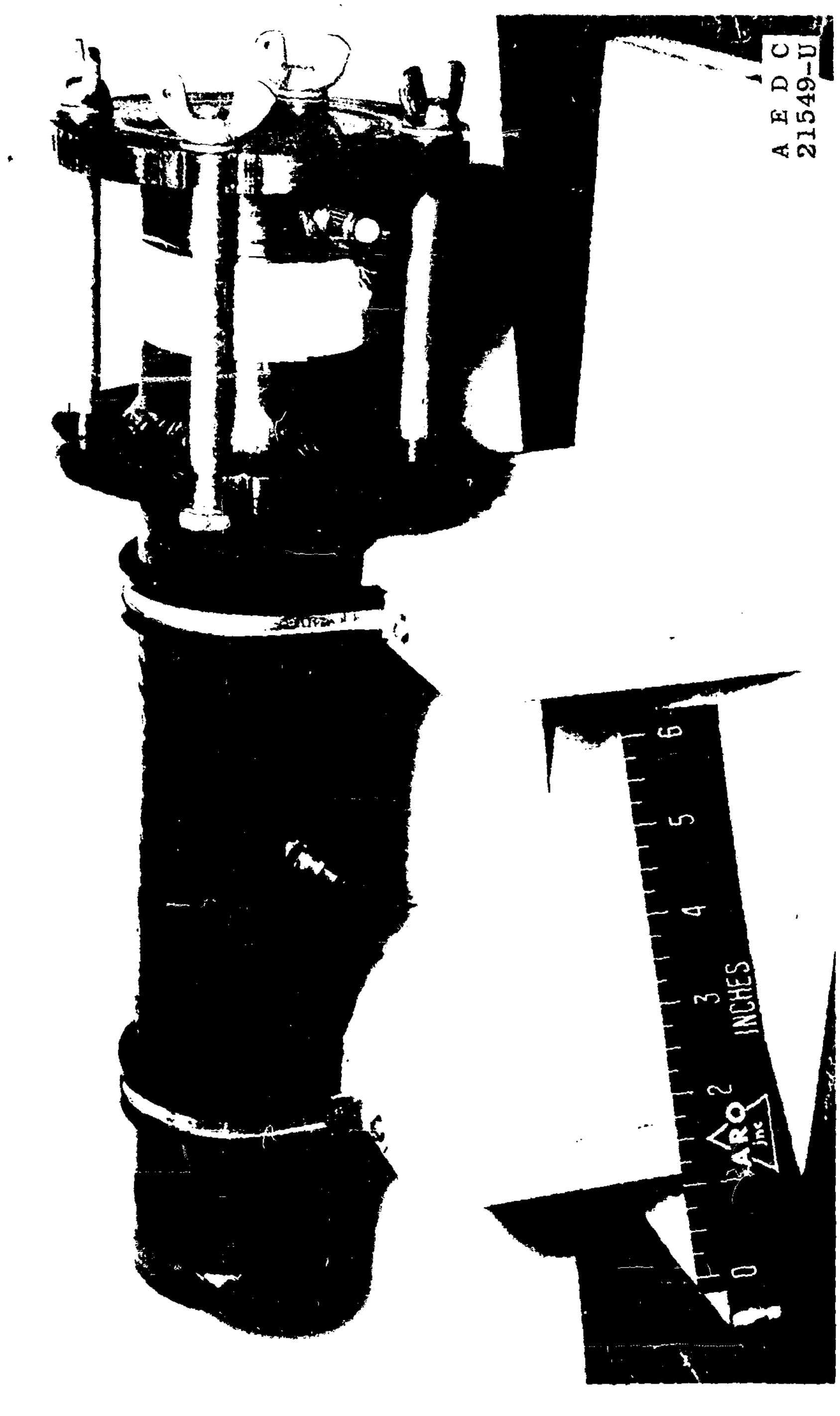

Fig. 6 Step Input Tube Assembly

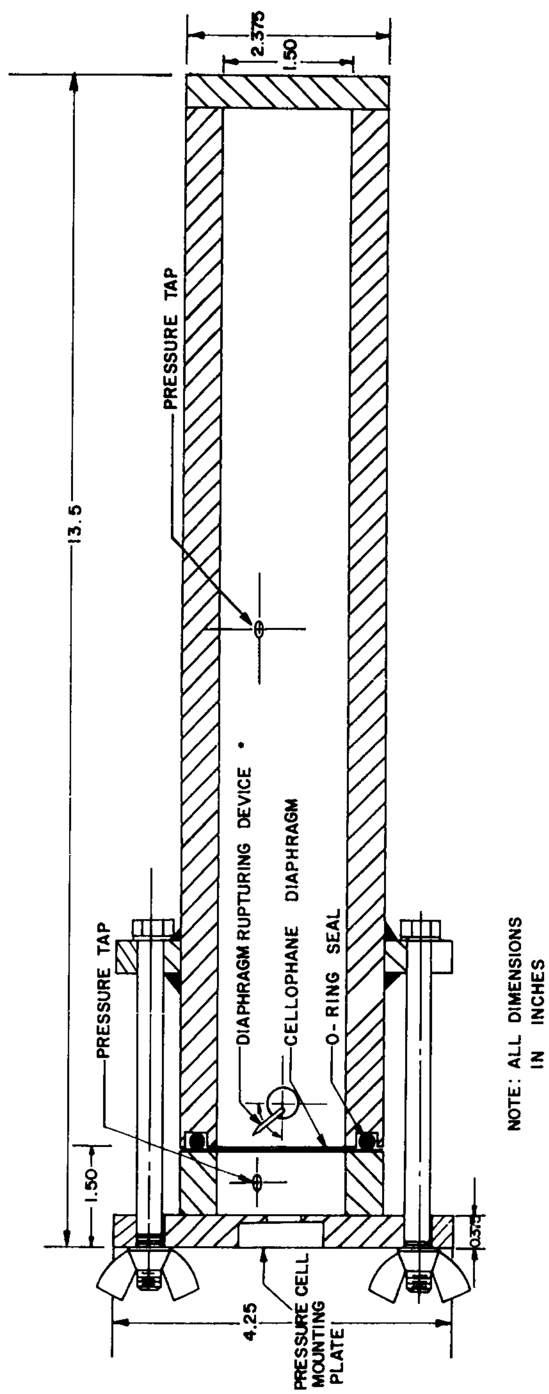

Fig. 7 Details of Step Input Tube

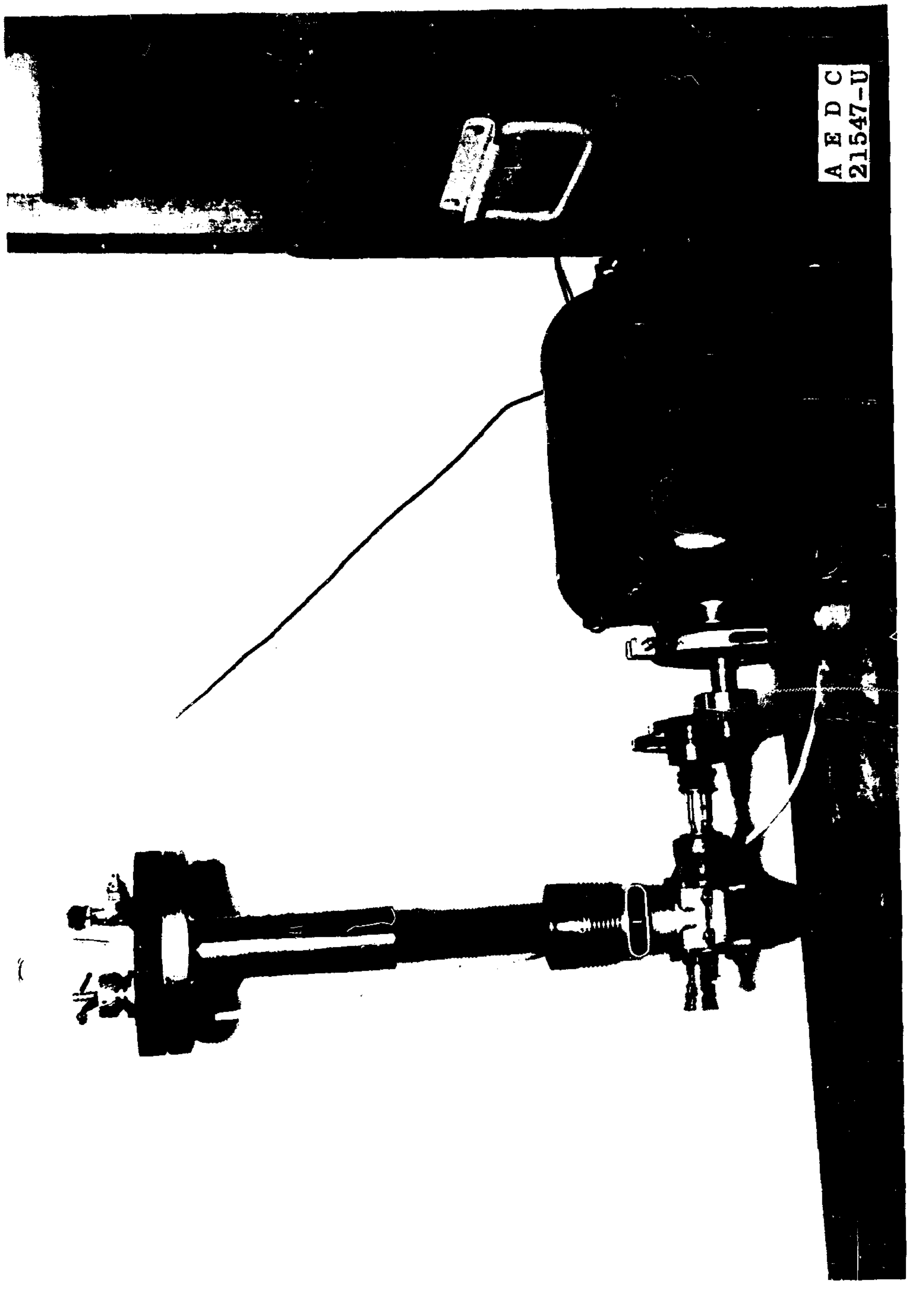

Fig. 8 Piston Calibrator Assembly

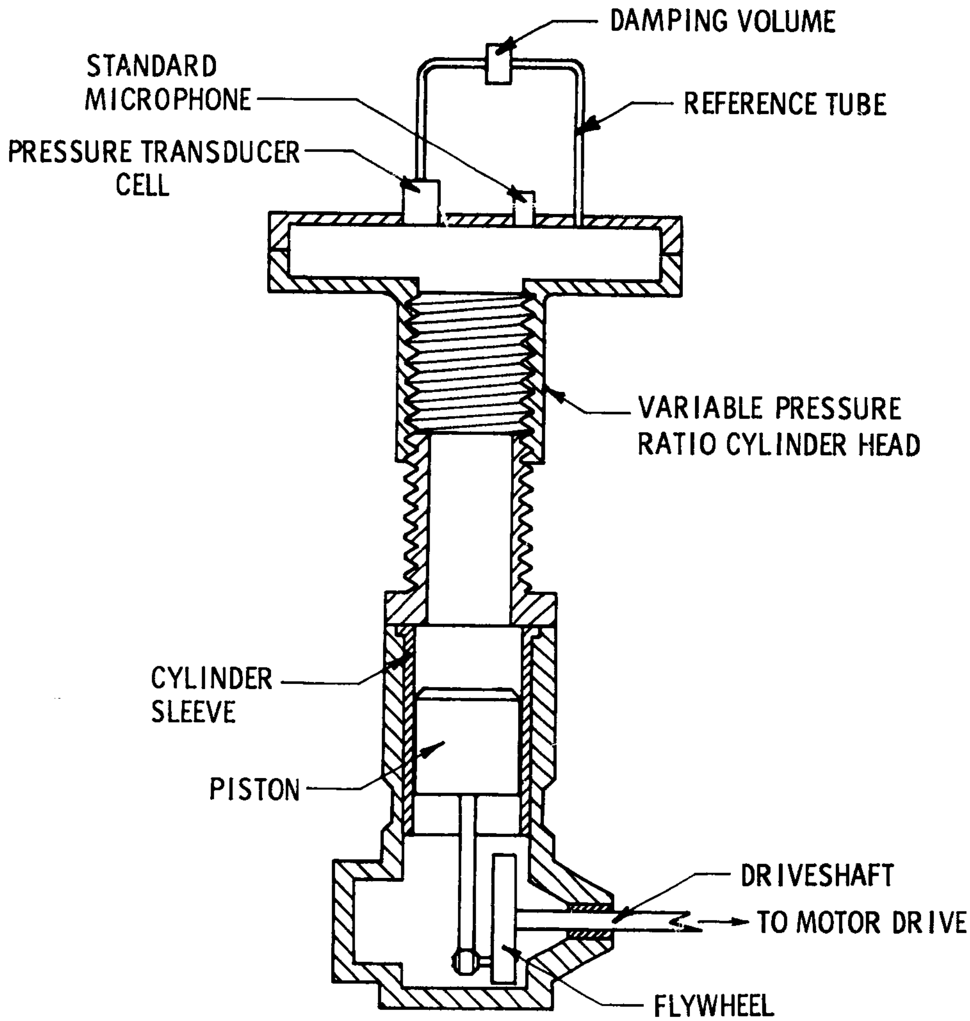

Fig. 9 Details of Piston Calibrator

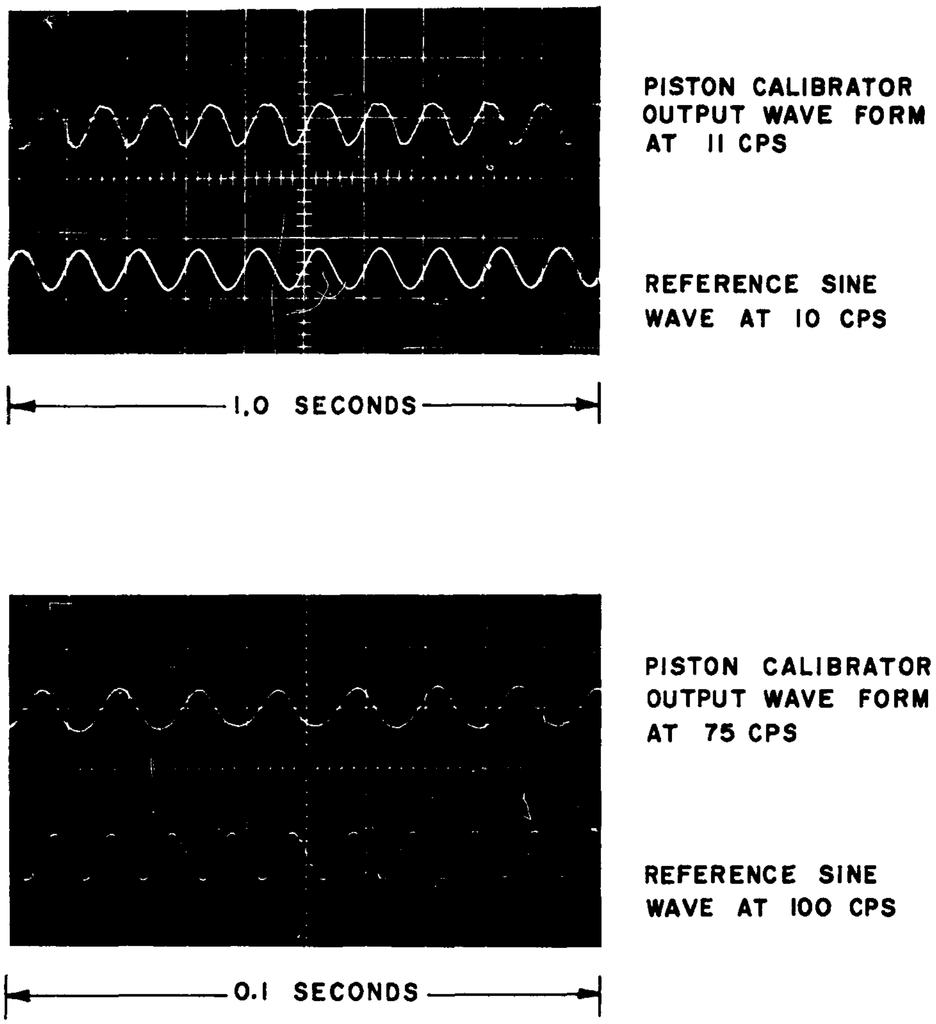

Fig. 10 Output Wave Forms of Piston Calibrator at Various Frequencies

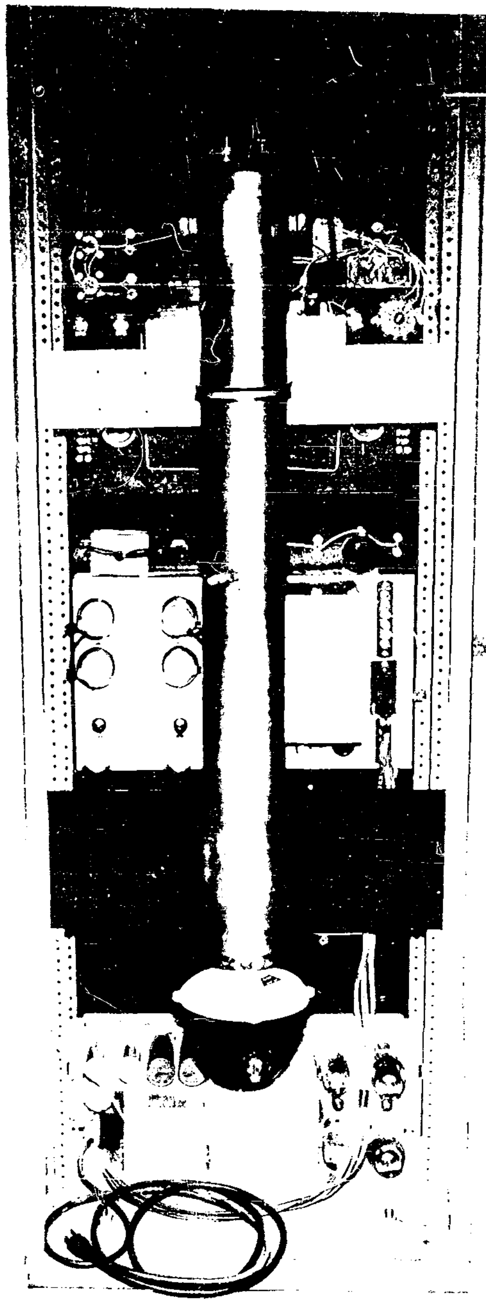

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Fig. 11 Standing Wave Tube Assembly

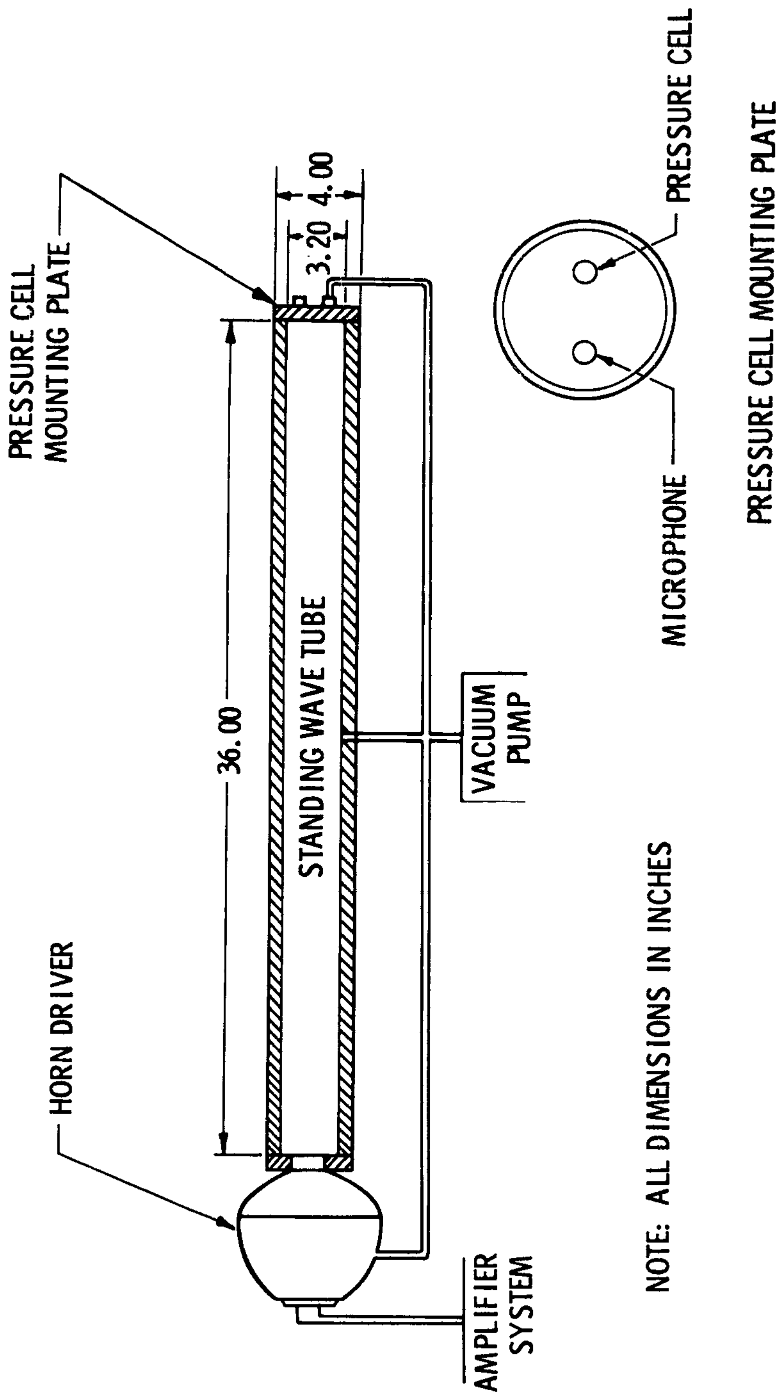


Fig. 12 Details of Standing Wave Tube

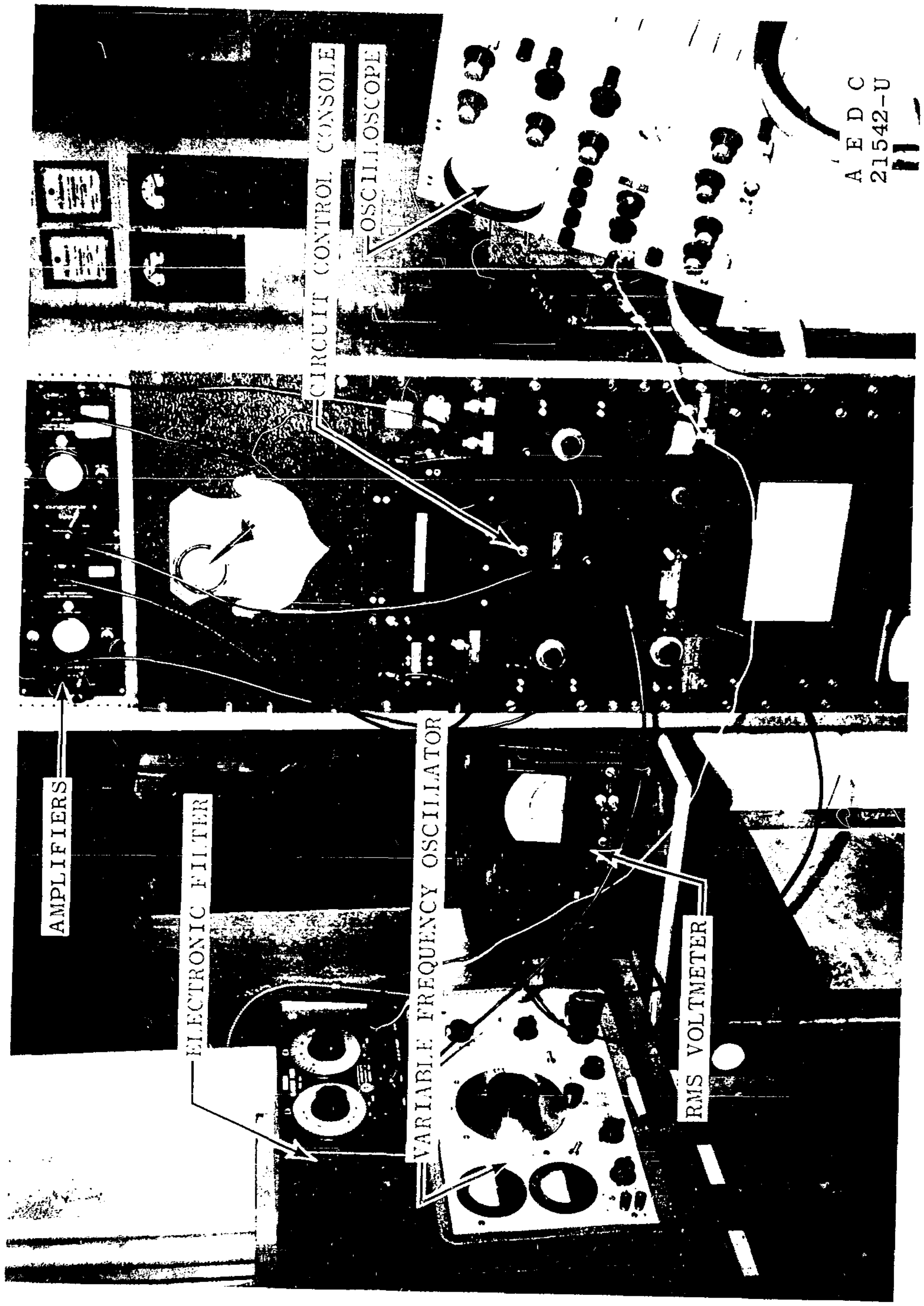


Fig. 13 Standing Wave Tube System Apparatus

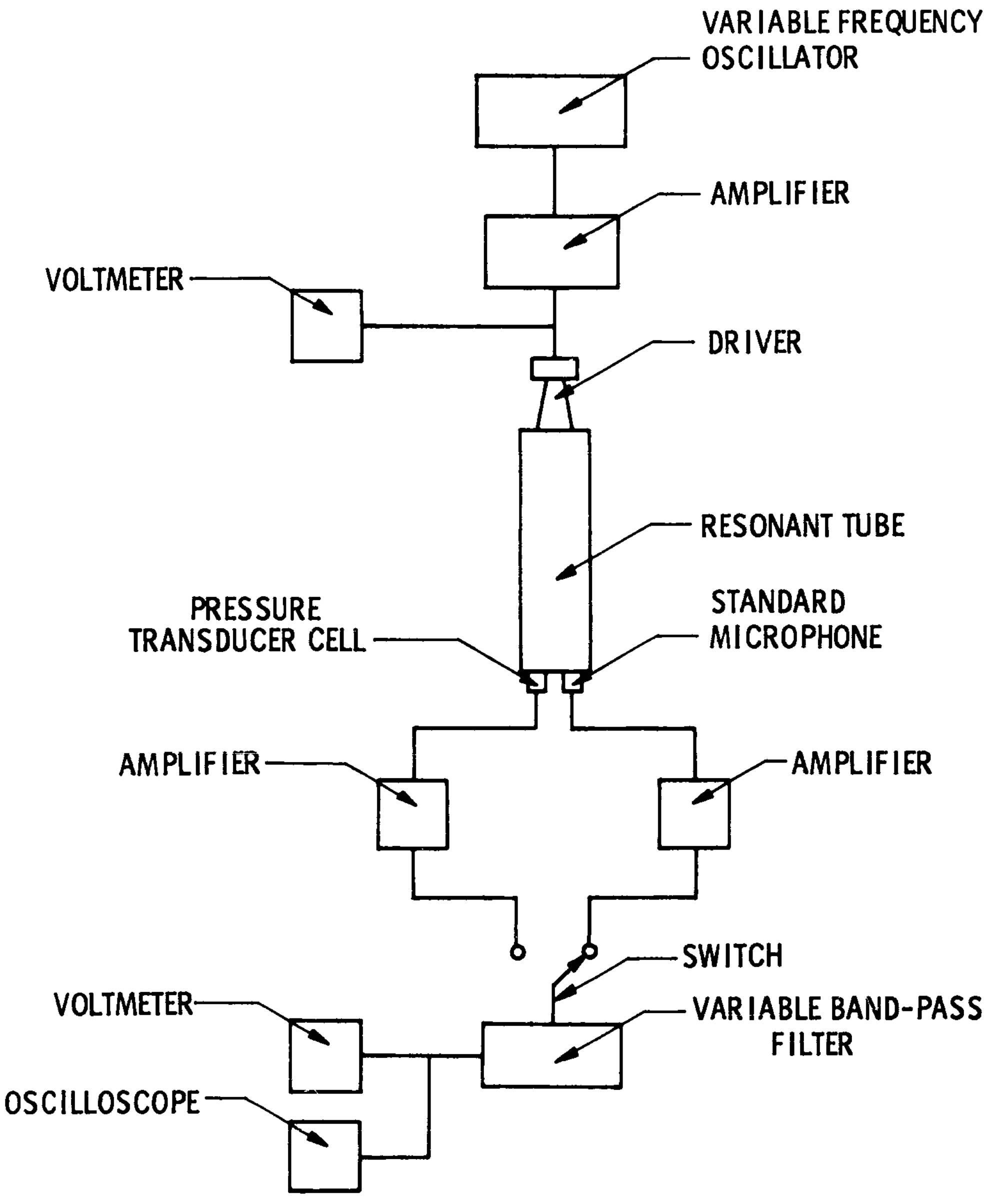


Fig. 14 Details of Standing Wave Tube System

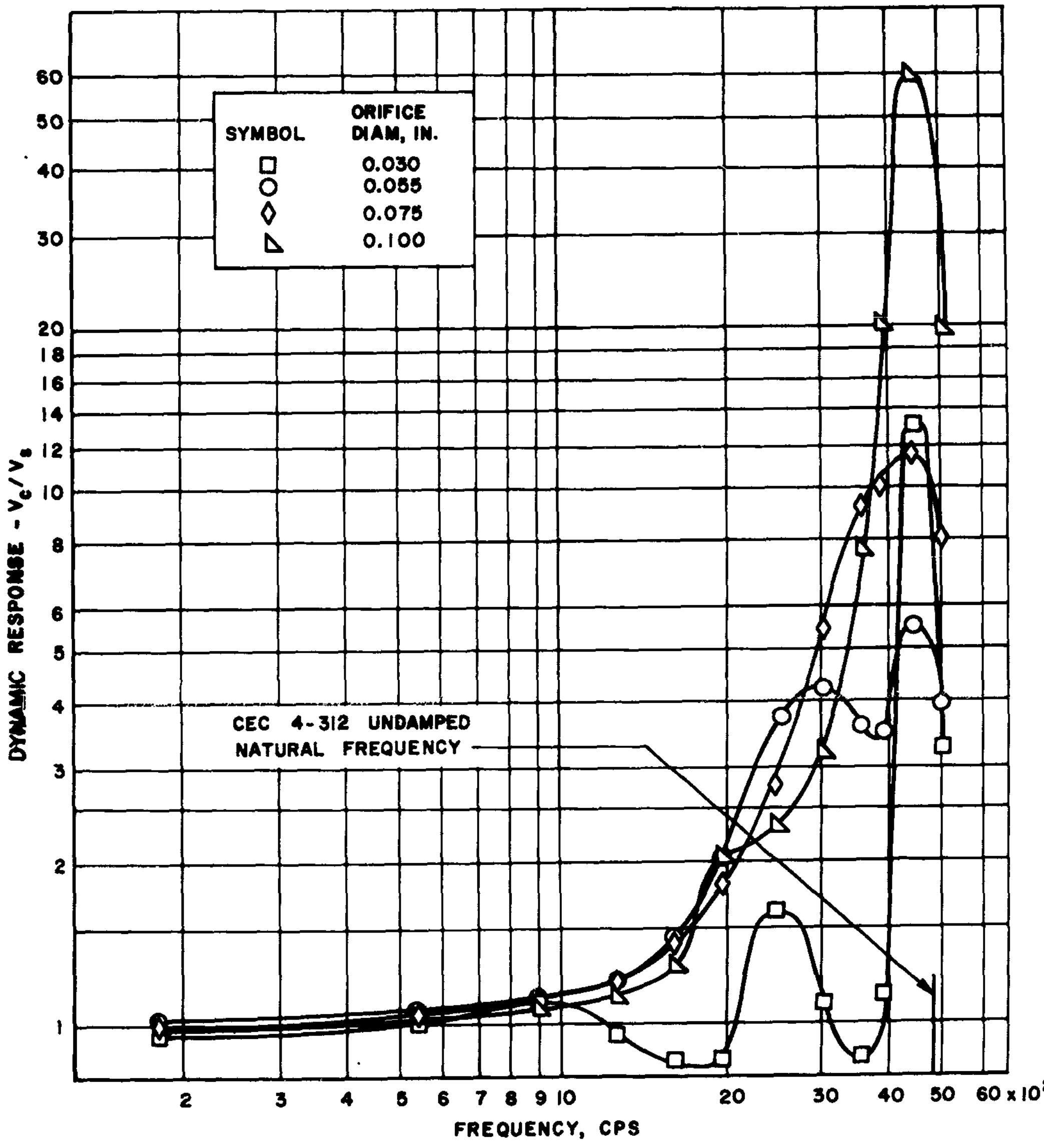


Fig. 15 The Effect of Inlet Oritice Diameter on the Dynamic Response of a Typical Pressure Cell of Constant Inlet Volume = 0.0137 in.^{3}

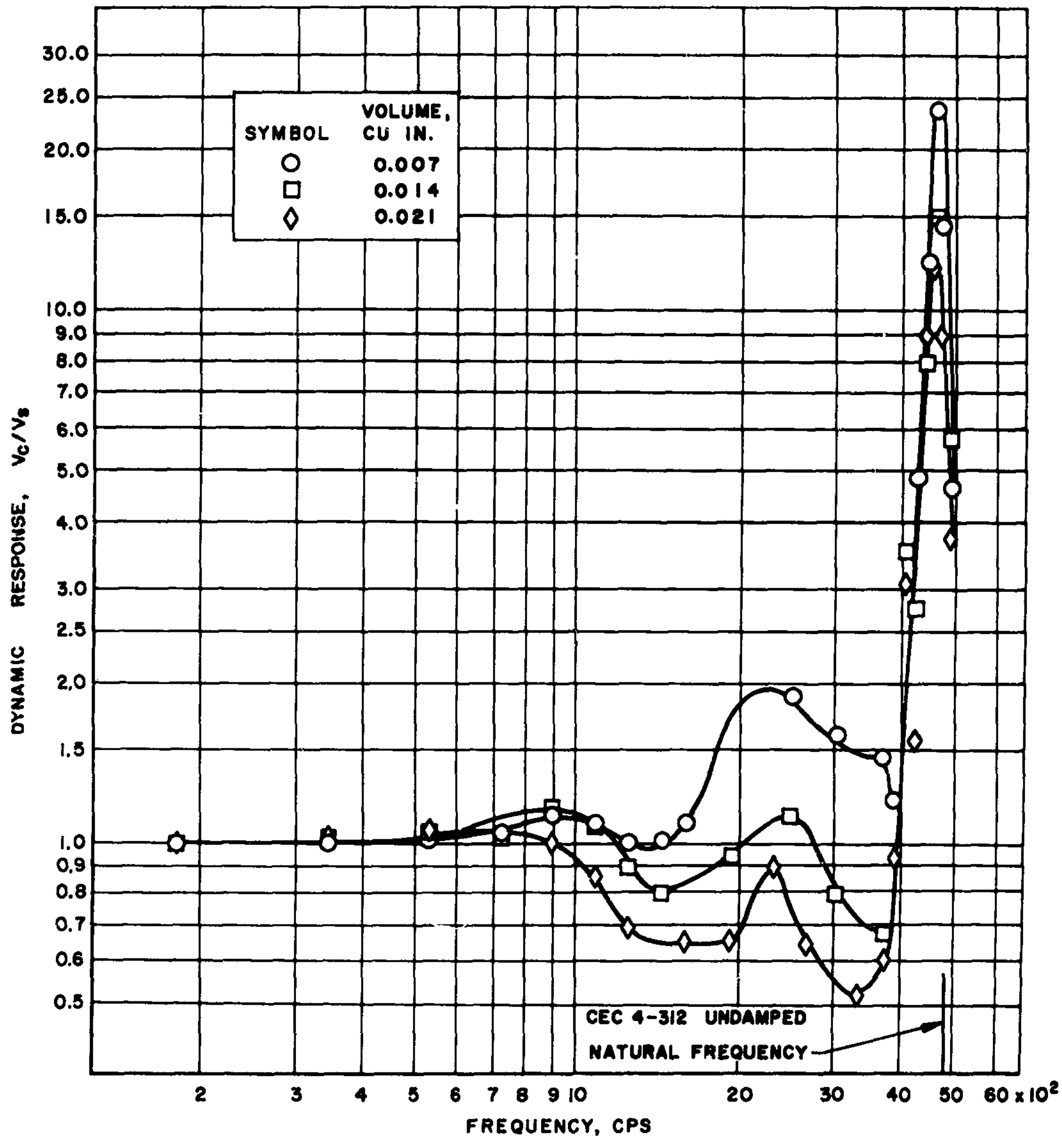


Fig. 16 The Effect of Inlet Volume Size on the Dynamic Response of a Typical Pressure Cell of Constant Inlet Orifice Diameter = 0.030 in.

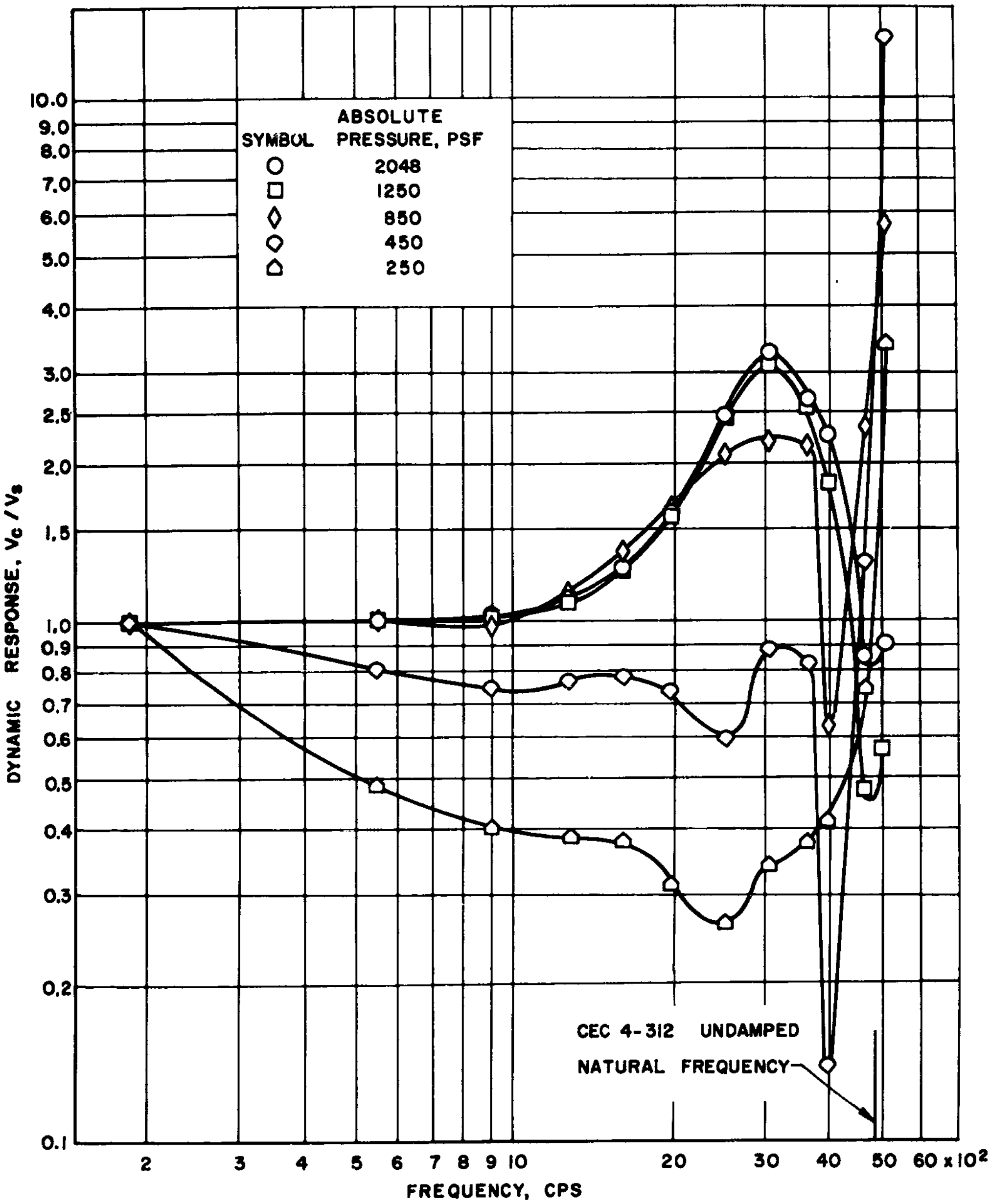


Fig. 17 The Effect of Environmental Pressure Level on the Dynamic Response of a Typical Pressure Cell of Constant Inlet Volume = 0.0035 in.^{3} and Orifice Diameter = 0.030 in.

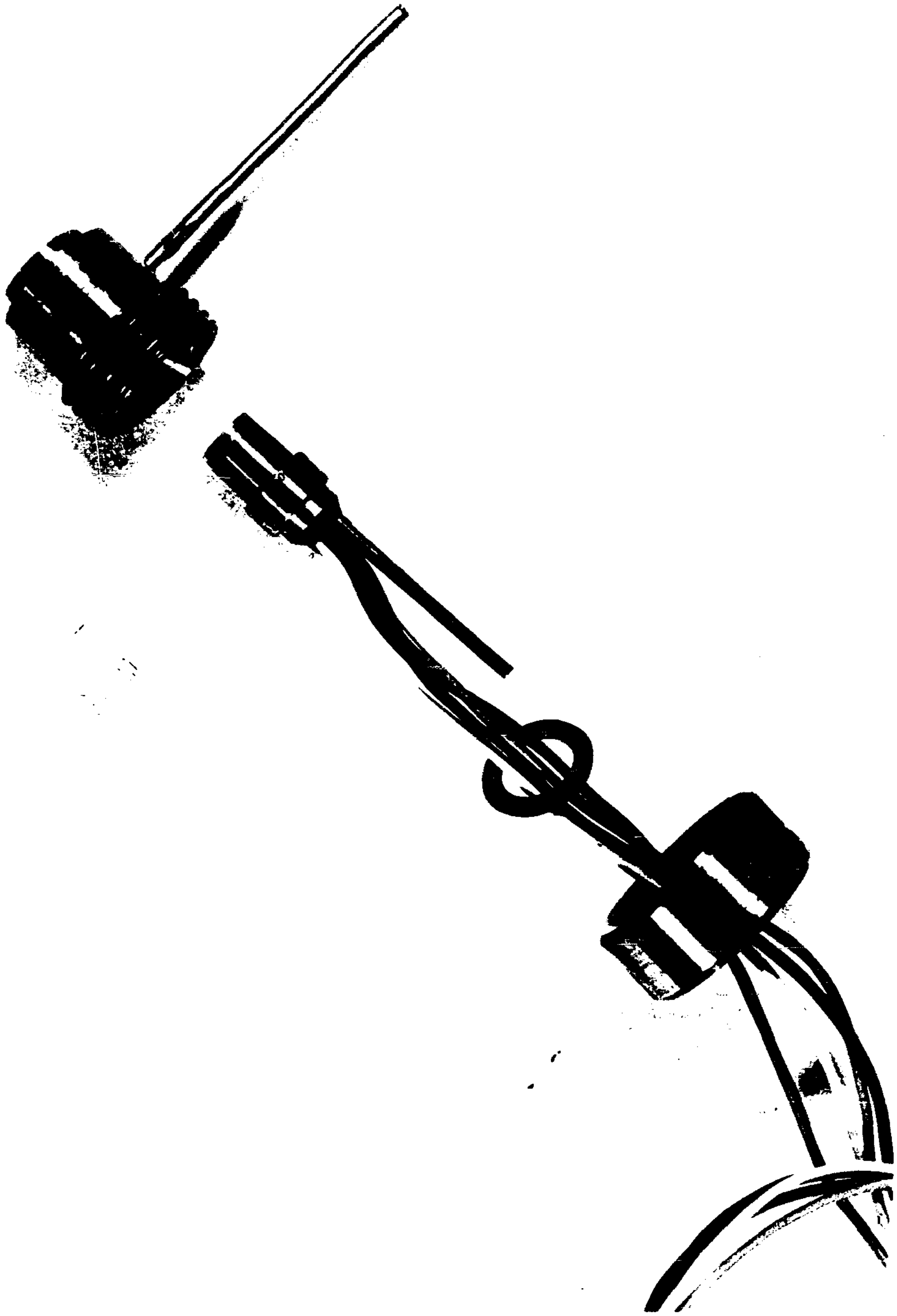


Fig. 18 Disassembled Pressure Transducer Cell System Adapted for Measurement of Unsteady Pressures on Wind Tunnel Models

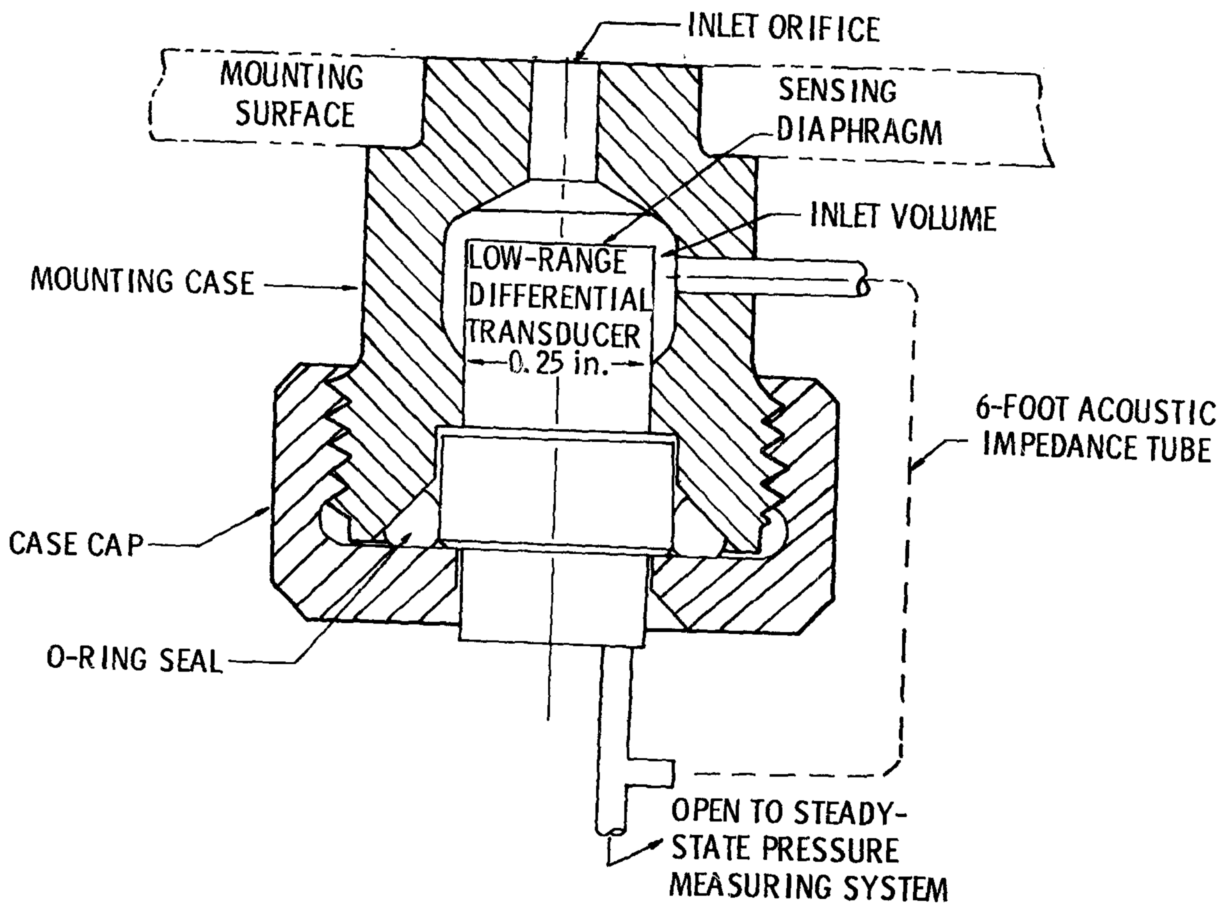
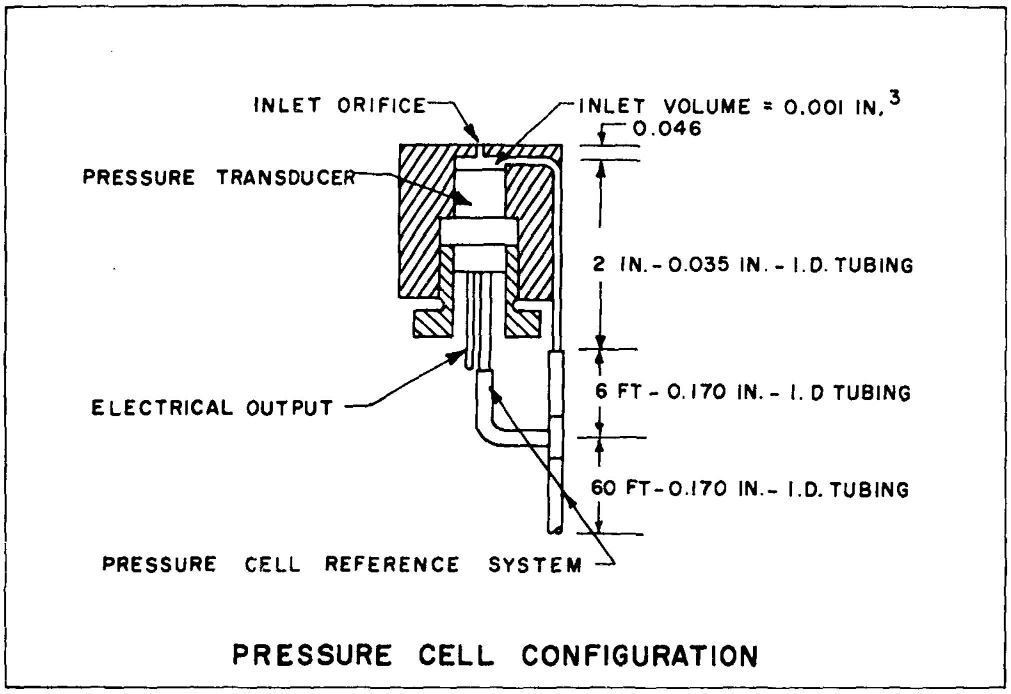


Fig. 19 Details of a Pressure Transducer Cell System Adapted for Measurement of Unsteady Pressures on Wind Tunnel Models



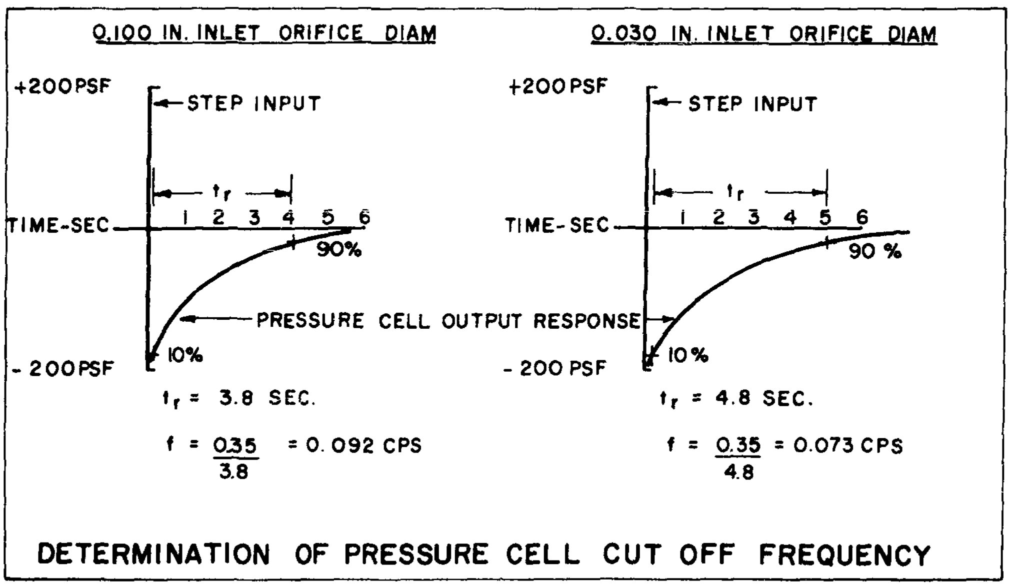
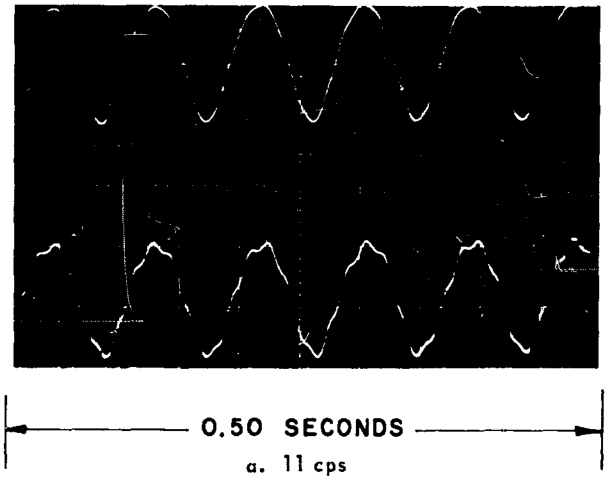
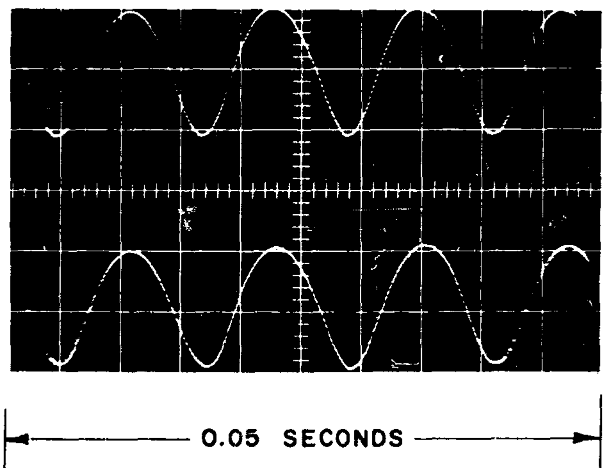


Fig. 20 Determination of Cutoff Frequency for a Wind Tunnel Model Pressure Cell Equipped with an Inlet Volume Reference Pressure System



a. 11 cps



b. 80 cps

Fig. 21 Output Wave Form of a Wind Tunnel Model Pressure Cell at Various Frequencies

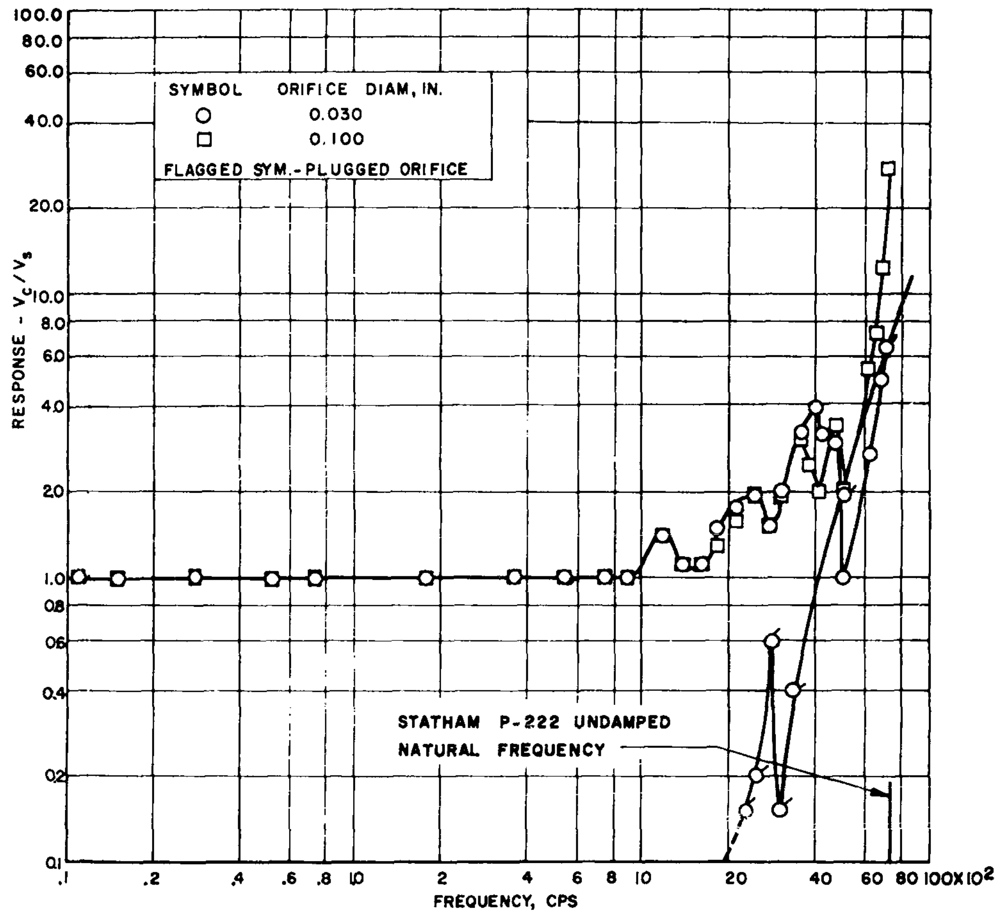


Fig. 22 Dynamic Response of a Wind Tunnel Model Pressure Cell of Constant Inlet Volume = 0.001 in.^{3}

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